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Fan Noise Research at NASA

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FAN NOISE RESEARCH AT NASA

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ABSTRACT

Results of recent NASA research to reduce aircraft turbofan noise are described. As the bypass ratio of a turbofan engine increases from 5 to as much as 20, the dominant source of engine noise is the fan. A primary mechanism of tone noise generation is the rotor blade wakes interacting with downstream stator vanes. Methods of analyzing rotor-stator tone noise generation are described and sample results are given. The role of an acoustic modal description is emphasized. Wind tunnel tests of model fans and nacelles are described including a novel rotating microphone technique for modal measurement. Sample far field results are given showing the effects of inlet length, and modal measurements are shown which point to a new generation mechanism. Concepts for active fan noise control at the source are addressed. Implications of the research which have general relevance to fan noise generation and control are discussed.

INTRODUCTION

Fan noise research as applied to quieting aircraft engines has been pursued by NASA for more than two decades. In particular, Lewis Research Center, which has responsibility for propulsion system research and technology, began working on quieting turbofans in the late 1960's as the first generation of high bypass turbofan engines was being introduced into the civil fleet. Substantial effort continued up until the early 1980's (Ref. 1) when a hiatus of roughly a decade occurred while efforts were directed to unducted, advanced turboprop configurations. With the advent of the decade of the 1990's, emphasis has returned to turbofan noise reduction research. In 1993, an Advanced Subsonic Technology (AST) Noise Reduction Program was initiated to develop technology to enable the next generation of commercial aircraft to meet more stringent noise rules. The three NASA aeronautics centers; Ames, Langley and Lewis; are jointly working with industry and academia to develop aircraft noise reduction technology. This paper gives a condensed overview of recent Lewis research efforts including NASA sponsored contract, grant, and in-house work with emphasis on the engine noise reduction portion of the AST Program.

The program includes a far term research emphasis on fans for ultra-high bypass ratio (BPR) engines ($10 < BPR < 20$) in combination with near term technology development which applies to current products (5 < BPR < 10). As engine BPR is increased beyond 5, the fan noise component becomes increasingly dominant in the total engine noise signature at both takeoff and approach conditions.

A cross-sectional view of an advanced, ultra-high bypass ratio turbofan engine concept is shown in Fig. 1 (Ref. 2). Acoustic treatment must be tailored to maximize fan noise attenuation within the constraints of minimizing nacelle weight and drag; consequently, treated length L per unit passage diameter D or duct height may be limited to values of L/D < 0.5, particularly in the engine inlet. Because the portion of the total noise reduction realizable by acoustic treatment is so tightly constrained, an inherently low source noise fan design is essential as represented in Fig. 1 by swept rotor blades and stator vanes which are spaced several rotor chords apart.

This review begins with a description of generation mechanisms and progress in predicting fan noise. Next, recent experimental model results are discussed; and a concept for active control at the source is described. Finally, relevance of the NASA turbofan work to other fan types is addressed.

FAN NOISE PREDICTION

For modern aircraft turbofans, a dominant generation mechanism at subsonic rotor tip speeds (approach and takeoff with power cutback) is rotor-stator interaction. The elements of a prediction/design system which is under development for rotor-stator interaction noise generation (Refs. 3,4) are shown in Fig. 2. Within the source region containing the fan stage, a chain of generation processes can be defined as shown in the flow chart beneath the engine cross section. A definition of rotor wakes/vortices is input to an unsteady aerodynamic gust response model for the stator. The output is the blade surface unsteady pressures which, in turn, are input to a duct acoustic mode coupling analysis to give the distribution of the amplitudes and phases of the annular duct modes. The acoustic intensity per mode propagated and radiated from the inlet and nozzle is then calculated by either finite element or finite difference codes which account for duct area change, the mean flow fields, and actual inlet and nozzle geometries. At present, the first generation source and inlet models for tone prediction are complete, and the aft radiation model is under development. Fan broadband models are also under development (Ref. 5).

A comparison of inlet tone predictions with data from a model fan (Ref. 6) is shown in Fig. 3. Two predicted inlet directivities which are nearly identical are shown: one obtained by applying the complete inlet analysis starting with the source, and the other obtained using measured acoustic mode content as input to the inlet radiation code. (The rotating microphone mode measurement technique will be described in detail in the "MODEL EXPERIMENTS" section.) Agreement between the measured and predicted directivities is good in the range of far field angles from 40° to 60°, but tone levels outside this range are underpredicted. Additional analysis using the full complement of measured acoustic modes showed excellent agreement over the full range of inlet angles indicating that fan sources in addition to rotor-stator interaction were present in the experiment (Ref. 4).

MODEL EXPERIMENTS

The experimental approach being used to study fan noise uses a model turbofan simulator in an anechoic wind tunnel to simulate flight conditions. Past test experience has shown that to obtain valid aeroacoustic data it is essential to simulate flight by either doing the experiments in a wind tunnel or by installing a specially designed inflow control device on the fan inlet during static tests (Ref. 1). Figure 4 shows a 17-in.-diameter fan model of an Advanced Ducted Propulsor (ADP) installed in the NASA Lewis 9- By 15-Foot Anechoic Wind Tunnel. Acoustically treated walls make the test section anechoic above about 250 Hz. Realistic fan models currently being fabricated for test are 22 in. in diameter corresponding to 1/5 to 1/6 scale relative to the largest full scale engines of interest (approx. 120-in.-diam. fan, 100 000 lb + thrust). At the low end of the commercial engine thrust range (about 5000 lb), the 22-in. diameter is essentially full scale. Figure 5 shows a cross-sectional view of the turbofan propulsion simulator to be used to drive the 22-in.-diameter fans (Ref. 7). The air turbine drive develops a maximum 4300 hp at 17 000 rpm. A rotating balance measures thrust and torque on the fan rotor, and a static six component balance measures axial force on the stator vane/cowl assembly.

An example of the type of acoustic data obtained in the 9- By 15-Foot Anechoic Wind Tunnel is shown in Fig. 6. In this case, the effect of fan inlet length on residual BPF tone directivity for a cutoff fan with 16 blades and 40 stator vanes is shown. As inlet length L decreases from an L/D of 0.53 to 0.21, the BPF increases from a low residual tone level representative of a cutoff condition to significantly higher levels (10 dB) as cutoff (an infinite duct length concept) begins to fail. This result implies that an approach that uses blade/vane ratios chosen for cutoff for fan inlet noise control on ultra-high bypass engines is problematic with short cowls.

As mentioned earlier, acoustic mode measurement is a powerful diagnostic tool to determine generation mechanisms and separate source and propagation effects when validating a fan noise prediction code. A unique rotating microphone probe has been developed for this purpose, and is shown installed on the ADP model in Fig. 7(a). The essence of the technique is that the probe rotates at a small precisely synchronized fraction (e.g., 1/250th) of the rotor speed (Refs. 8,9). Since each annular mode spins at a unique velocity, in the reference frame of the rotating probe Doppler shifting splits a single fan tone into a series of "tones" which can be distinguished in a high resolution narrow band spectrum of the probe signal. Each "tone" corresponds to an individual circumferential mode. Measurements of amplitude and phase at multiple radial locations allow radial mode content to be determined. Extraneous modes due to the probe wake interacting with the fan all appear in the circumferential mode number equal to the fan blade number and can be rejected (Ref. 9).

A sample measured modal distribution in terms of circumferential and radial mode orders m and n is shown in Fig. 7(b). The condition corresponds to the modal content at BPF for 16 rotor blade wakes interacting with 22 stator vanes—a cuton situation expected to generate modes at $m = -6$. The amplitudes were normalized by multiplying them by the cosine of their respective propagation angles with respect to the duct axis in order to better indicate their energy flux to the far field. Of course phase information, not shown, is also important in determining far field levels. The most striking feature of Fig. 7(b) is the presence of many additional extraneous modes at m orders not associated with rotor-stator interaction. Subsequent detailed examination of the fan case at the tip revealed circumferential discontinuities at multiples of four per revolution which could impulsively vary rotor loading to generate the extraneous mode content. When the total measured mode content at 9600 rpm (data similar to Fig. 7(b)) was inserted as input to the inlet radiation code, the discrepancies between predicted and measured tone levels in Fig. 3 were essentially resolved (see Fig. 9 of Ref. 4). Thus, the value of having mode measurement capability for mechanism verification can be critical in any noise reduction experimental program.

ACTIVE NOISE CONTROL AT SOURCE

Active control of turbofan noise is particularly difficult because, for most frequencies of interest, the sound field to be controlled consists of higher order spinning circumferential/radial modes far from the plane wave limit. Therefore, active cancellation of the sound propagating in the inlet or fan duct inherently involves many actuators spaced axially and circumferentially if higher order modes are to be cancelled without the undesirable "spill-over" generation of extraneous mode power.

Because of these difficulties, an alternate approach was investigated in which active control is applied directly at the source to prevent the generation of propagating acoustic modes. Figure 8 illustrates the concept in the form of actively controlled compliant stator vanes to prevent rotor-stator interaction noise generation. Specifically, locally controlled actuators on the vane surface are driven such that the unsteady blade surface pressures associated with the gust response to the rotor wakes is modified to prevent the generation of propagating acoustic modes.

The results of a numerical experiment to demonstrate this concept are shown in Fig. 9 (Refs. 10,11). Figure 9(a) shows the unsteady pressure contours calculated with a two-dimensional gust response code for a cascade of loaded airfoils, i.e., blades with thickness and camber. The circumferential and axial cascade coordinates, η and ξ, are measured in units of stator chords. Single acoustic modes propagating both upstream and downstream from the cascade are evident from the nearly parallel contours indicating regular wavefronts. Figure 9(b) corresponds to the case where active control on the vane surfaces was effected by placing two small "pistons" 0.1 chord long on each blade at the 0.2 chord position on the suction surface and 0.8 chord position on the pressure surface. An analytical procedure was applied to determine the piston motion necessary to completely cancel both propagating modes. No evidence of the propagating acoustic modes remains in the pressure field shown in Fig. 9(b). While the development of this concept is at an early stage, the calculated potential warrants experimental investigation.

RELEVANCE TO OTHER FAN TYPES

One can ask the question as to what aspects of the NASA fan noise research program directed at aircraft engine noise reduction have relevance or potential application to industrial fan noise control. Early findings (Ref. 1) of the importance of controlling inflow distortion or upstream wakes and vortices using flow conditioners consisting of honeycomb/screen structures may be useful in some industrial applications. Once the flow disturbances experienced by the fan are restricted to internal sources, the task of applying noise prediction/design codes of the type described in the "FAN NOISE PREDICTION" section becomes much more tractable. On the experimental side; a reliable, practical acoustic mode measurement technique such as the rotating microphone method is indispensable in diagnosing the dominant generation mechanisms in any particular application. Inexpensive versions of this apparatus are possible for industrial applications where more benign environments are encountered as compared to the turbofan case with its combination of high Mach number flows, rotor speeds and intensity levels. Active noise control has already shown success in those industrial applications which are essentially plane wave environments. However, the concept of control at the source could lead to advantages such as simultaneous upstream and downstream cancellation with only one set of actuator locations.

SUMMARY OF CONCULSIONS

This review of NASA fan noise research has emphasized the current approaches to reducing this often dominant noise component of turbofan propulsion systems for commercial transports. Key components of the program are: (1) the development of fan noise prediction/design codes based on modeling the essential physics of the generation, propagation and radiation processes; (2) the conduct of realistic and, therefore, scalable model tests; (3) the development of acoustic mode measurement techniques as essential to generation mechanism identification; and (4) the exploration of active noise control concepts particularly emphasizing the potential for control at the source. Some thoughts on the relevance of this work to industrial fan noise control problems were also given.

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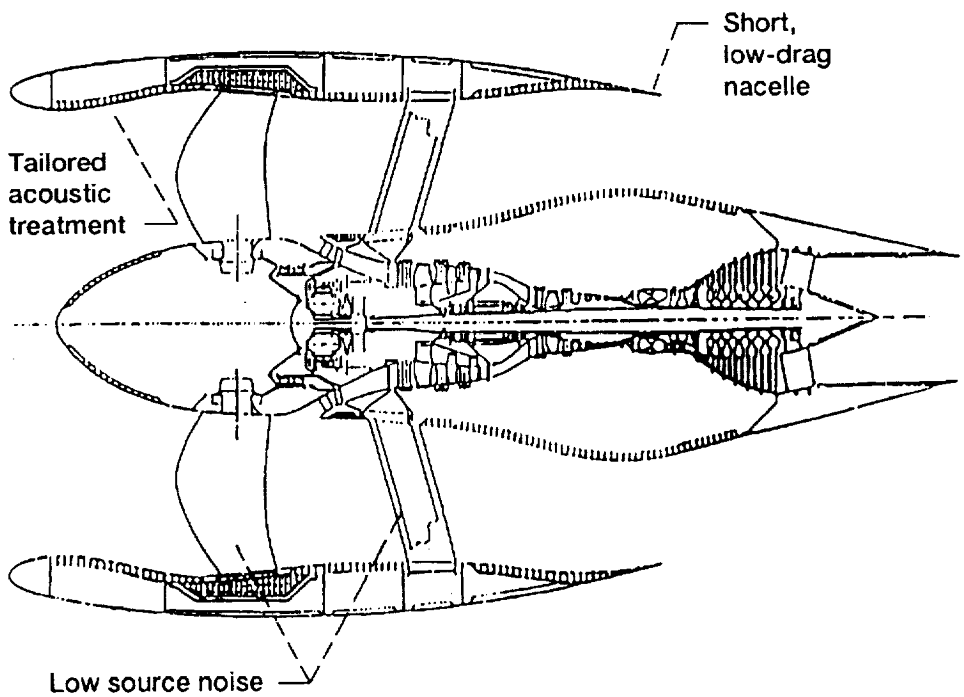

Figure 1.—Ultra-high bypass turbofan (bypass ratios, 10 to 20+).

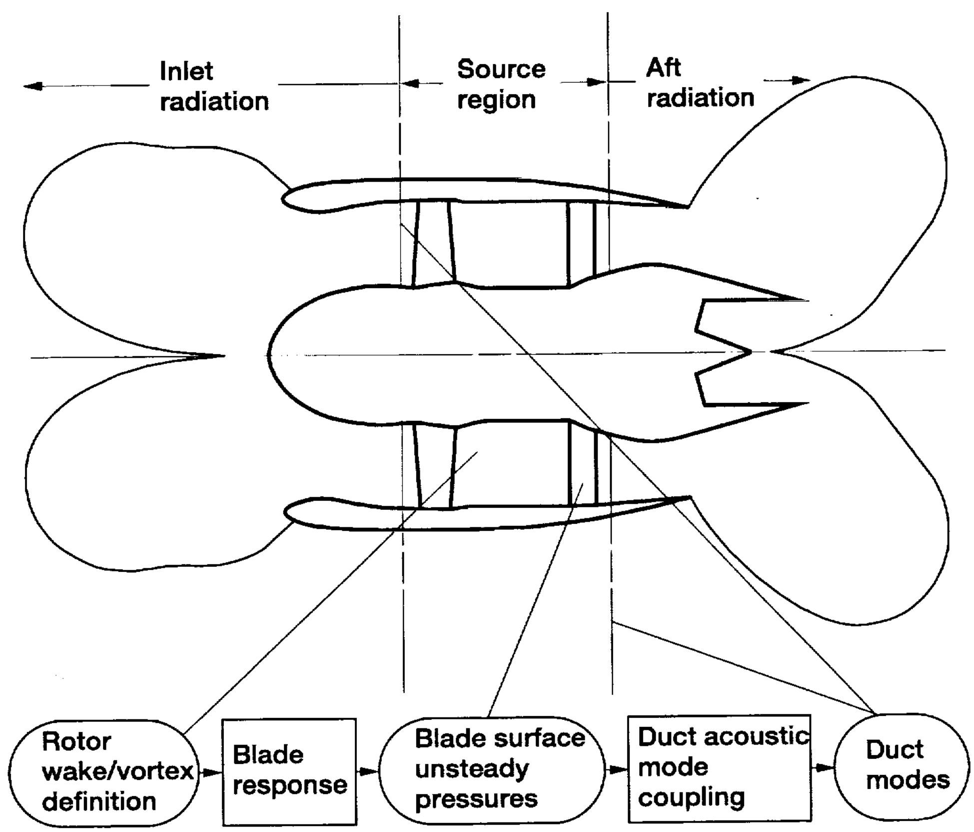

Figure 2.—Fan noise prediction/design system; rotor-stator interaction.

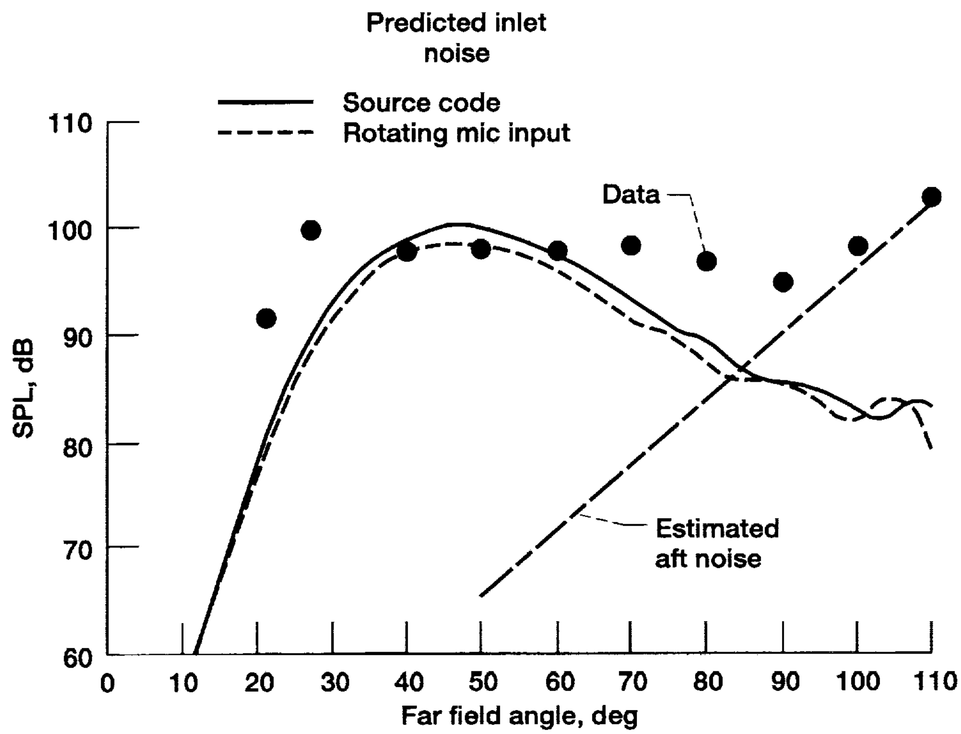

Figure 3.—Fan tone predictions versus data at BPF, ADP 17 in. model, 9600 rpm, 22 vanes, 2 chord spacing, medium inlet.

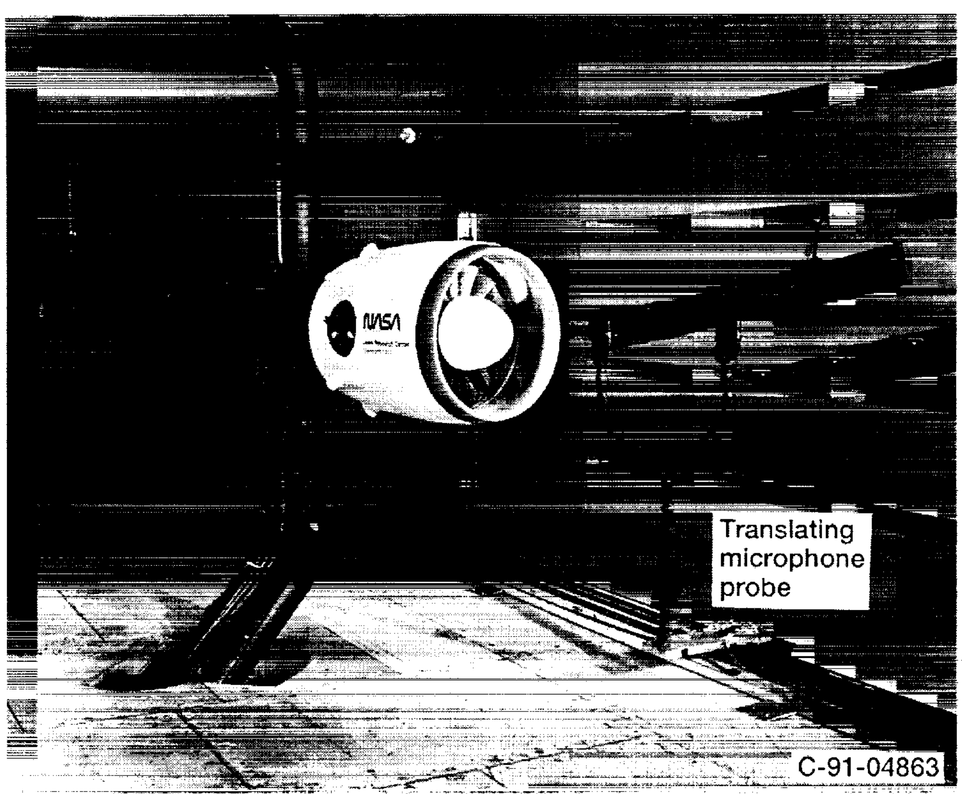

Figure 4.—Advanced ducted propulsor installed in Lewis 9- x 15- ft anechoic wind tunnel.

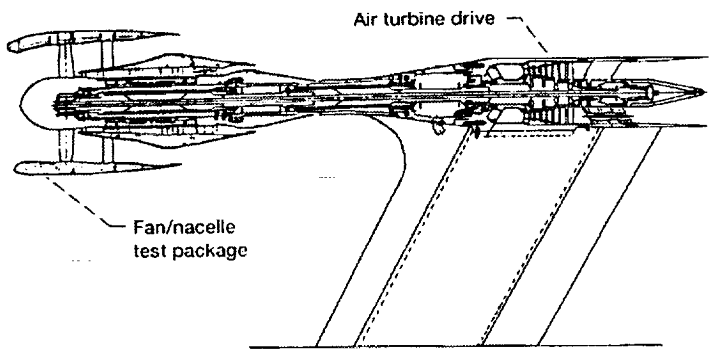

Figure 5.—Turbofan propulsion simulator.

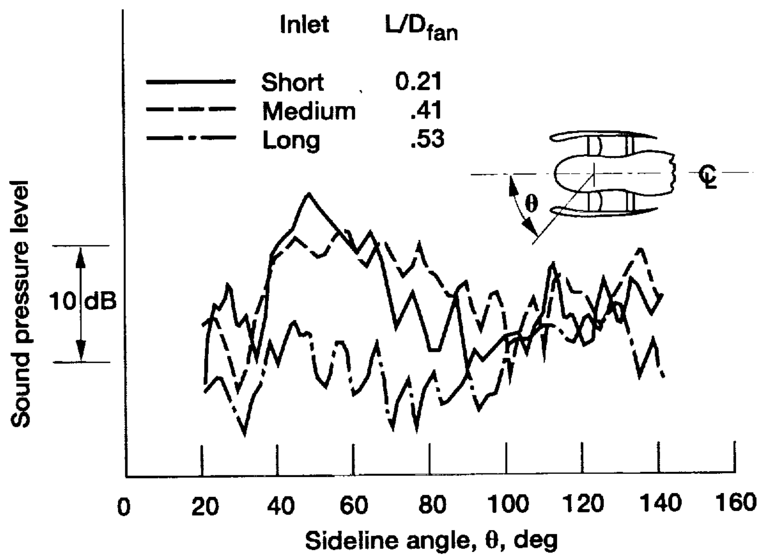

Figure 6.—Effect of inlet length on BPF tone directivity. 40-vane stator, 107% speed, $\alpha = 0°$, $\beta = -11°$, M = 0.2.

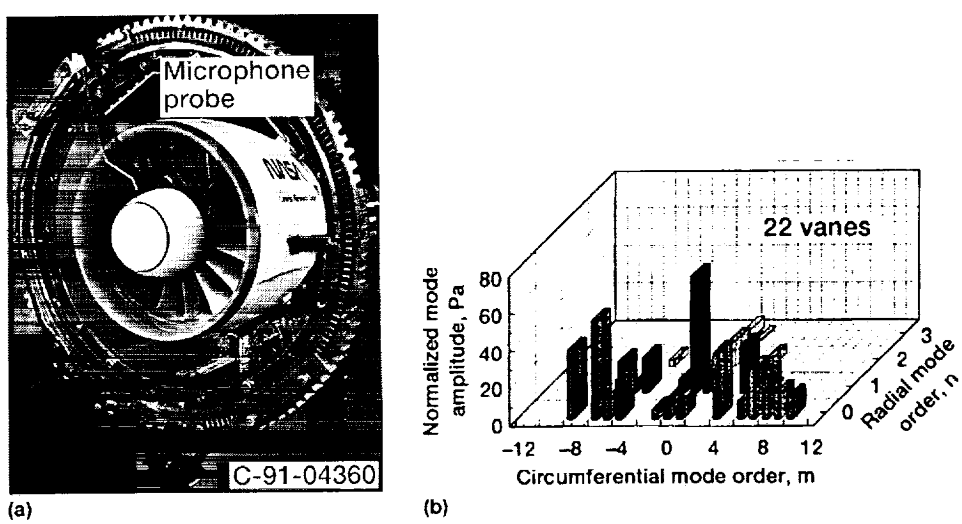

Figure 7.—Fan acoustic mode measurement. (a) Rotating mode probe installed on advanced ducted propulsor model. (b) Measured fan inlet BPF modal distribution, M_t = 0.77, 11400 rpm, long inlet.

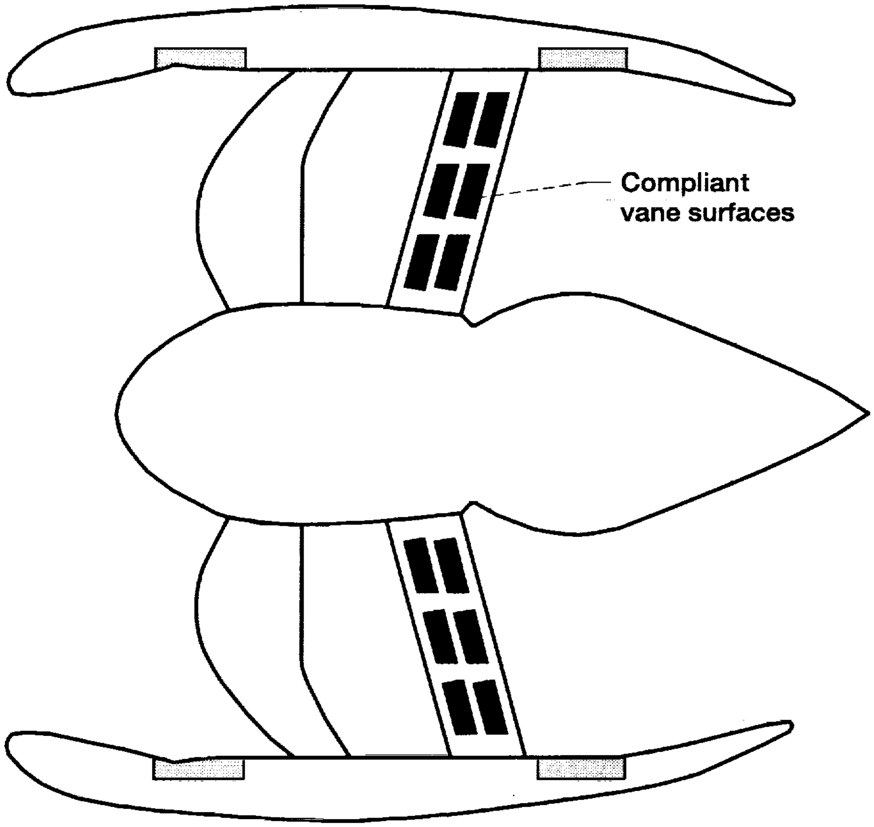

Figure 8.—Active fan tone noise control by compliant stator vanes.

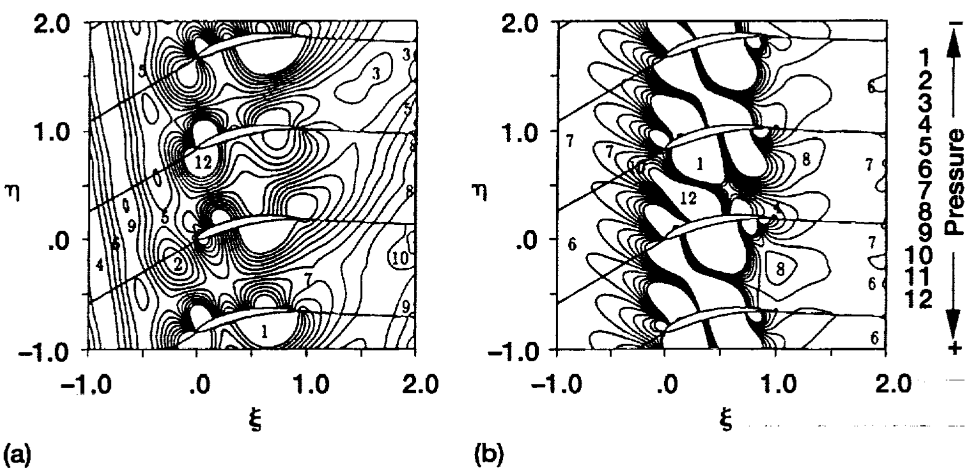

Figure 9.—Calculated stator vane unsteady pressure fields at 2 BPF. (a) Without active control. (b) With active control, 2 actuators/blade, 0.2 chord suction/0.8 chord pressure surfaces.

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